planets that survive the Sun's red giant phase are likely to remain stable for longer than a billion years (possibly much longer), and those of the Jovian planets are likely to remain stable for more than 10 billion years (possibly much longer). Pluto is likely to escape from its current 2:3 mean-motion resonance with Neptune within a few billion years beyond the Sun's main-sequence lifetime if subject only to gravitational forces; its prognosis is even poorer when nongravitational forces are included. Higher mass stars, which lose a larger fraction of their mass during their red giant phase, may lose their planetary systems as a consequence of their mass loss.

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Virtual Reality on Mars Pathfinder

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The objective of this project was to produce a three-dimensional (3-D) photo-realistic virtual reality (VR) model of the Martian surface for use in the Mars Pathfinder mission. Marsmap, the interactive terrain visualization system, creates and renders digital terrain models produced from stereo images of Mars' surface taken by the lander's images for Mars Pathfinder (IMP) camera. A primary benefit of using VR to display geologic information is that it provides an improved perception of depth and spatial layout of the remote site. The VR aspect of the display allows an operator to move freely in the environment, unconstrained by the physical limitations of the perspective from which the data were acquired. Virtual reality also offers a way to archive and retrieve information in a way that is easily understood. Combining the VR models with stereo display systems can enable a feeling of presence at the remote location. The capability, implemented in Marsmap, to interactively perform measurements from within the VR model, offered unprecedented ease in performing operations that are normally time consuming and difficult using standard photogrammetric techniques. This ground-breaking project demonstrated the power of using VR as a cartographic tool.

In the rapid production of digital terrain models (DTMs), a computational algorithm called the "stereo pipeline" was used. The core component of the stereo pipeline is the automatic matching of features in the left-eye camera image with the same features in the right-eye camera image, thus providing the necessary correspondence to compute a 3-D location for the feature. A significant aspect of the project was the rapid production and display of models by using a distributed production team and fast data transfer. The first complete stereo panorama sequence taken after deployment of the IMP, known as the "Monster Pan," was composed of 98 stereo pairs. These data were displayed in VR at mission control at the Jet Propulsion Laboratory within 1 hour of downlink.

The Pathfinder DTMs were displayed with an interactive user interface called MarsMap which includes the following key features: (1) real-time, interactive navigation of the virtual viewpoint through the 3-D model of the landing site; (2) measurement of topographical features, including 3-D positions, distances, and angles; (3) display of daily traverses of Sojourner; (4) display of rover images within the VR model projected from the viewpoint of the rover; and (5) catalog and display of the sequence and location of science experiments conducted by the rover.

MarsMap was designed to be accessed with a standard 2-D mouse and used pull-down menus to call features. Models could be viewed in stereo using Stereographics Crystal Eyes liquid crystal display shutter glasses or with a set of head-tracked "Virtual Binoculars." The two figures show example views of the Martian surface generated using MarsMap.

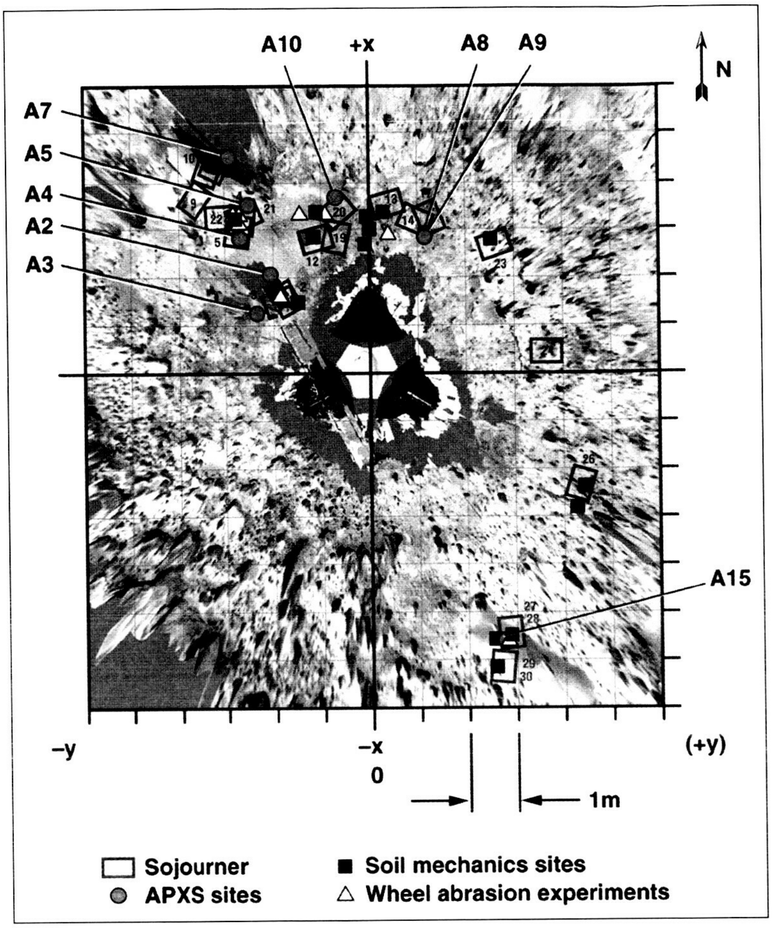

Fig. 1. Overhead view of the Pathfinder landing site. Data markers indicate the positions of rover activities through the first 30 sols of the mission including rover end-of-day positions (red rectangles), APX measurements (blue dots), soil mechanics experiments (black squares), and wheel-abrasion experiments (yellow triangles). (1 sol on Mars is the equivalent of 1 Earth day or represents one complete rotation of the planet.)

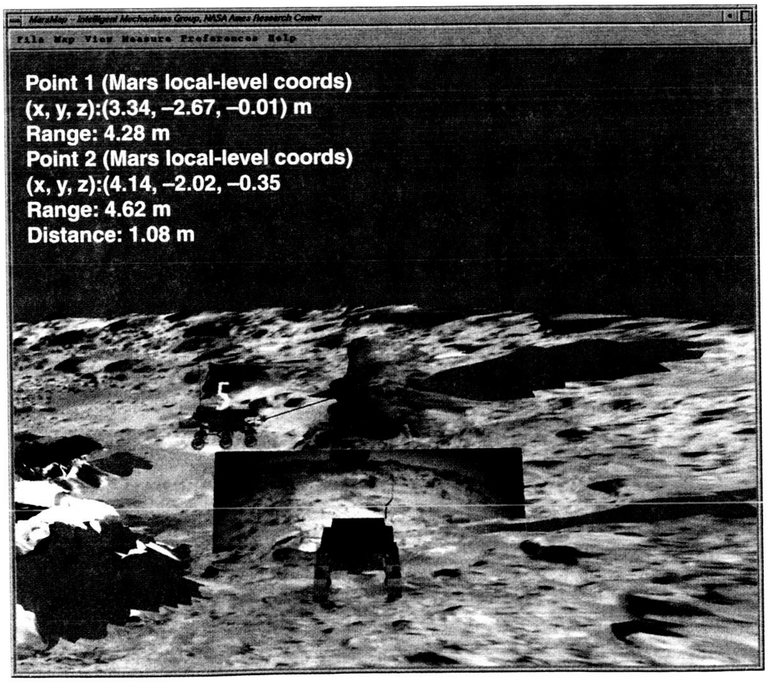

Fig. 2. Two views of MarsMap showing (a) a measurement of a rock, and (b) a rover image projected into the 3-D model.

Beyond the spectacular visualization capabilities for navigating Mars in 3-D, MarsMap provided the Pathfinder team with a valuable tool for performing mission planning and operations, science analysis, and public outreach. The Marsmap project has shown that VR can be used as a powerful method for analyzing the geology of a remote environment. Virtual reality models can be created and displayed, and analysis and measurements can be performed with unprecedented speed and accuracy. Virtual reality may represent a giant leap forward for scientific analysis.

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Cratering Rates on the Galilean Satellites

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In the inner solar system, impact craters are made mostly by asteroids and long-period comets. The Jupiter family of comets, whose comets are in relatively short-period, low-inclination orbits dominated dynamically by gravitational interactions with Jupiter, is relatively unimportant. These roles are reversed in the outer solar system. Asteroids rarely reach as far as Jupiter, and long-period comets are more or less uniformly distributed. The Jupiter-family comets, which swarm about Jupiter, are relatively the most important source of cratering in the vicinity of Jupiter. The purpose of this project was to determine the absolute cratering rates on the Galilean satellites, and to use those rates to estimate surface ages on Io, Europa, Ganymede, and Callisto.

Cratering rates are determined by the numbers and sizes of the comets, by their distribution in space, by their impact probabilities with the various objects, and by their impact velocities. The most important uncertainty is in the size-number distribution of the comets. This must be determined from the properties of observable comets, which are mostly comets that pass near Earth. It has recently become possible to perform extensive numerical simulations of statistically significant numbers of comet orbits as they evolve from their source region in the Kuiper belt to their many fates. These models fill in the orbital distribution of the comets, such that one can calibrate the distribution as a whole to the relatively few comets that are large enough or come near enough Earth to observe.

A single sentence summary of this work is that 20-kilometer-diameter craters, which are made by kilometer-size comets, occur on a Galilean satellite about once in a million years. The uncertainty in this rate is a factor of 5. More than 90% of the craters on the Galilean satellites are caused by the impact of Jupiter-family comets. Long-period comets contribute at the 1%–10% level, as do the Trojan asteroids (asteroids that are coorbital with Jupiter, trailing or leading Jupiter by ±60 degrees). Main belt asteroids are currently unimportant, for each 20-kilometer crater made on Ganymede implies the disruption of a 200-kilometer-diameter parental asteroid, a destruction rate far beyond the resources of today's asteroid belt.

Study results are presented in the figure. All data are expressed in terms of the equivalent number of 10-kilometer craters. The curves are the surface ages that correspond to these crater densities at these apex angles—solid curves are ages relevant to Ganymede, the dotted curves are ages relevant to the higher cratering rate at Europa—calculated according to the assumption that the satellites have been in synchronous rotation throughout. The surface ages are those predicted using a nominal cratering rate, with the additional assumption that the Kuiper belt decays inversely with time. Ages for Callisto are not shown, but are consistent with the age of the solar system.